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The Death Knells of Mature Technologies

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ABSTRACT

The oscillatory behavior in the mature phase of some technologies' diffusion-related S-curves are investigated, specifically with regard to the influences that other technologies can have on the oscillations. The notion of mortality indicators is raised, i.e. whether such behavior is a signal that the mature technology is under attack from an emerging technology. The case of structural panels in the wood products industry is considered as an example, and an updated forecast of the substitution of oriented strand board for plywood is made. It is concluded that factors such as macroeconomic business cycles are primarily responsible for the oscillations in plywood's S-curve, although it is argued that an emerging technology can also contribute to perturbations in a mature technology's S-curve. Two possible alternative explanations for the oscillatory behavior are also discussed, viz. a previously proposed chaos-formulation and a mathematical model based on modified Lotka-Volterra equations. This model shows that oscillatory behavior in mature technologies' S-curves can also result from symbiotic interaction between two technologies under certain circumstances.

Introduction

Oscillatory behavior in the mature phase of the diffusion-related S-curves of technologies is a phenomenon that has been recognized and discussed in the literature. One of the reasons why this type of oscillatory behavior is of more than passing academic interest, is the question whether the oscillations signal the demise of the mature technologies, i.e. whether they are mortality indicators for mature technologies, as has been proposed previously in the literature. Mortality indicators of mature technologies can be useful not only in the search for new

technologies, but also in the development and execution of end-game strategies for mature technologies In this paper we address the question whether the oscillations are indeed mortality indicators, or in the general case, whether they are in some way triggered by the interaction with another technology Although this paper does not attempt to speak the final word on the subject, it adds to the debate by considering two cases

In the first case, that of plywood being "attacked" by oriented strand board (OSB)/waferboard, it is shown that the oscillatory behavior in plywood's S-curve correlates very well with the fluctuations in the residential fixed investment pattern in the US, and it is concluded that this macroeconomic effect rather than the emergence of OSB causes the oscillations in plywood's S-curve This leads to the conclusion that oscillatory behavior per se is not a mortality indicator in the sense described above However, it is possible to identify some perturbations in the S-curve that can be ascribed to the emergence of a new technology

In the second case, a conceptual model is developed to illustrate the more general case of interaction of one technology with another Other authors have argued that the oscillatory behavior in the mature phase of an S-curve may be a chaotic effect However, these arguments have not taken into account the interaction of another technology with the technology exhibiting the oscillatory behavior In this paper, a mathematical model is formulated to show that the symbiotic interaction between two technologies can also give rise to chaos-like oscillatory behavior in S-curves This conceptual model is offered to illustrate another (but not necessarily the only) possible cause for the oscillatory behavior The model is based on modified Lotka-Volterra equations, and differs from the chaos formulation in that the

interaction among two technologies is explicitly accounted for here, rather than just modeling one technology competing against the market

Mortality indicators of mature technologies

The identification and tracking of emerging technologies have important implications for a company from a strategic viewpoint. As major new technological innovations create new industries and destroy old ones, it is essential that firms formulate strategies and deploy resources in a timely fashion. New technologies bring with them the requirements for new strategies, new organizational structures and new measures of competitiveness. From the viewpoint of managing a company's R&D effort, for example, early warning of an emerging technology obviously can aid in the selection of projects, indicate which research directions to pursue and which to stay clear from. Similar issues are of concern to directors of public research institutions and policy makers. Barbé *et al.* have done research to examine the way companies perceive new technologies *vis-à-vis* its competitors and the consequences of the companies' responses [1 as quoted by 2]. They found that the earlier a company perceived the threat of a new technology, the more flexible its range of strategic responses was. They conclude that it is important for a company to gather and process information as soon as possible before competitors erect barriers to entry. Similar arguments can be made to show the importance of identifying emerging technologies from a national rather than company viewpoint.

Relying on chance successes is not a satisfactory way of going about the search for emerging technologies. This is particularly relevant when one considers the fact that new technological innovations very often originate from outside a particular industry which it impacts (see for

example [3]) The implication is that there is no obvious place to look and furthermore it is very difficult to determine if something that is detected is actually a new technology that is "emerging" Once such an emerging technology has been identified, however, there are various ways in which one can keep track of its progress, all with their different strengths and weaknesses A systematic framework for gathering and processing data is a much more rewarding strategy than grasping for straws in the wind Several structured approaches that can be employed to aid in the search for emerging technologies have been suggested (see for example [4-9], to mention only a few)

Rather than directing the search at the new emerging technology itself, however, it may be advantageous to use an indirect route by *focusing on the demise of mature technologies* From the accumulated knowledge base on the processes of technological innovation, especially the diffusion of technology and the substitution of one technology with another, we know that the rise of an emerging technology is often associated with the demise of an older, more mature technology In this regard, Foster speaks of *attackers* and *defenders* [10] Relying heavily on S-shaped growth curves, he shows how an older, defending technology can be attacked by a new, emerging technology In the case where the new technology is attacking an older, established technology in a particular market niche, one can thus argue that *if it is possible to detect signals that a mature technology is "dying", such signals may indicate that a new technology is emerging* If this hypothesis is true, the identification of *mortality indicators* of mature technologies can be a powerful technique to aid in the identification of emerging technologies It will be particularly useful in generating clues suggesting where to search for emerging technologies, since the market niche has now been identified The ability to identify indicators which show when an older technology is under attack from an emerging technology

can be equally useful from the viewpoint of the company that has an interest in the older technology, since such a company will have to formulate and execute an appropriate and timely response to the attack [11] In order to pursue this line of reasoning, it thus becomes necessary to investigate the characteristics of mature technologies, particularly with the aim of finding signals that indicate that the mature technology is being attacked by a new, emerging technology Such mortality indicators will be particularly useful if they can be identified in real time

To illustrate the concept, consider for example Modis and Debecker's findings on patterns of active service contracts in the mini-computer industry [12] They examined the service life cycle of computers and found that the cumulative sales of computers follow S-shaped curves, but that the service lives of the same computers follow so-called end-of-life curves The latter take explicit account of the mortality of products In their analysis Modis and Debecker kept track of the number of active service contracts for certain generations of computers, noting that hardware maintenance contracts for computers closely follow systems sales Initially the number of contracts increases at the same rate as sales However, whereas cumulative sales follow the logistic S-curve, the number of active contracts reaches a peak and then starts declining as machines age and become obsolete Modis and Debecker point out that the *graph depicting active service contracts peaks before the cumulative sales does* As an explanation for this phenomenon, they argue that " the total number of units sold of a particular product increases with time, reaching a ceiling at the end of the product's life cycle The number of products *in use*, however, never reaches the same ceiling as there is a certain mortality among the products sold" They found that computer generations are replaced due to technological obsolescence because of aging per se, and confirmed the notion that computer models are

phased out as a generation, as opposed to personal cars, for example, that are phased out individually. Computer models thus phase out as their generation becomes outdated, independently of when they were sold.

In the case of computer models, the number of service contracts may thus prove to be a mortality indicator for mature technologies. Although there are certainly many aspects and characteristics of mature technologies that can be investigated as potential mortality indicators, we shall concentrate on one particular phenomenon in this paper, viz. the oscillatory behavior that is sometimes detected in the mature phase of the diffusion-related S-curve of some technologies.

Oscillatory behavior in S-curves

The S-curve is a very well known concept in innovation management and hence it will not be elaborated on here in any detail, save to mention that it has application in explaining diffusion, substitution as well as technological progress. There is strong empirical evidence that in many cases, the diffusion of a technology over time displays a smooth growth pattern — in fact, that is the whole notion underlying the shape of the S-curve. However, the actual data points very often exhibit erratic behavior in the sense that they deviate from the smooth curve. Although some of these deviations can be ascribed to measurement error, many of them cannot, and therefore must be ascribed to other influences. The deviations often exhibit a clear oscillatory behavior in the mature phase, and it is to these oscillations that we now turn our attention. Just as the rate of diffusion of a technology can be ascribed to many factors (see [13-19], for example), one can now also ask what causes the oscillatory behavior in the mature phase of growth curves.

Several authors have commented on fluctuations that some growth curves develop as they enter the mature phase, among them Montrey and Utterback [20], Marchetti [21], Modis and Debecker [22], and Modis [23, 24] With regard to the oscillatory behavior in the mature phase of the S-curve, Modis states " At the extremities of the substitution process deviations from the logistic growth pattern have been observed As the substitution approaches completion — above 90% — the trajectory pattern breaks into random fluctuations" [24] Marchetti notes that " these logistics or quasilogistics can become oscillatory when approaching saturation (a possible solution of Volterra equations often appearing in ecological contexts)" [21] These comments support the notion that the appearance of oscillations in the mature phase of some technologies' S-curves is a recognized phenomenon Montrey and Utterback, however, go further and lay the seed for the hypothesis that such oscillations may actually indicate the emergence of a new technology attacking the old Referring to the oscillations in the mature phase of plywood's S-curve, they state " . We venture to hypothesize that the type of variance in production of a commodity, such as shown for plywood in recent years is a clear sign of the vulnerability of that product to an emerging substitution such as the one depicted for waferboard and oriented strand board (OSB) The same pattern appears in charts of sales of several other commodities such as aluminum" [20] The questions now arise whether the oscillations in the mature phase of a technology's S-curve are mortality indicators and if so under which circumstances

Figure 1 shows the sales of plywood and OSB/waferboard in the US Note how the growth curve of plywood grows smoothly (with minor oscillations), but then breaks into pronounced oscillations in the mature phase, and how the emergence of a new technology

(OSB waferboard) coincides with the onset of oscillatory behavior in the S-curve of the mature technology (plywood in this case). Since external factors such as those referred to in a earlier in this section have such an important influence on the rate of diffusion, is it reasonable to assert that they, or other external factors, will also cause or influence the oscillations? If so, this would weaken the argument that the oscillations are triggered by the emergence of an emerging technology. For example, Girifalco points out that erratic behavior from the smooth S-curve can be attributed to changes in the business, political and social environments or to the specific differing characteristics of the adopters [25]. Davies has shown that the growth curve exhibits oscillatory behavior due to the fact that the industry (niche) is expanding or contracting [17]. A chaos formulation has also been proposed by Modis and Debecker, and is discussed later in this paper. From a mortality indicator viewpoint, however, the question that arises is whether these oscillations are brought about by the emergence of a challenging new technology in some way or another. If so, is this a necessary, sufficient and unique condition for the oscillations? Obviously if one can show that the oscillations are triggered by the emergence of a new technology (and *only* by the emergence of a new technology), it will be an extremely powerful and useful indicator with profound implications on the ability to identify and track emerging technologies as well as end-game strategies for mature technologies. Alternatively, the weaker case where an emerging technology also influences (but is not solely responsible for) the oscillatory behavior in a mature technology's S-curve is also useful, although less so and more complicated to apply operationally.

Diffusion of plywood and OSB/waferboard

Montrey and Utterback investigated the diffusion of plywood and OSB waferboard in the light frame construction industry [20,26]. This case is discussed here as an illustrative example for

several reasons, viz it is a good example of oscillatory behavior in a mature technology's S-curve, it illustrates the interaction between two technologies within this context (as opposed to just one technology competing against the market) and it has drawn some discussion in the literature

After World War II, and particularly since the 1950s, plywood became the dominant structural panel in the industry, having gradually displaced lumber as the preferred sheathing material for floor, wall and roof construction However, since the late 1960s several developments led to the appearance of new unveneered panels (notably waferboard and OSB) that started challenging plywood's dominance [20], viz.

- *Technology related developments* There were process advancements for the manufacture of chip or flake based panels
- *Raw material developments* The prices of plywood were increasing fast, due in part to the depletion of suitable timber supplies for the manufacture of plywood On the other hand, suitable new timber supplies for unveneered panels were being exploited at lower costs Lately there has also been some environmental pressures that tend to limit the raw material supply of plywood
- *Market developments* The remaining raw material supply for plywood had been declining in quality
- *Political developments* There had been some changes in building codes that made the unveneered panels more acceptable

The new unveneered structural panels were mainly waferboard, COM-PLY and OSB Waferboard was first produced in Canada in 1966 and then spread to the US COM-PLY was

first marketed in 1976, but had not proven to be a very successful product and has almost disappeared as a serious competitor OSB has been commercially produced since 1981 and has been very successful It has proven to be superior to waferboard and in some respects also to plywood All three of the plywood substitutes are marketed as structural sheathing commodities Montrey and Utterback concluded that plywood was, and would continue to be, at a severe cost disadvantage with regard to the newer panels, and that there was no doubt that plywood was under attack from the newer panels [20]

OSCILLATORY BEHAVIOR OF THE S-CURVE

Consider now again Figure 1 which shows the sales of plywood and OSB/waferboard in the US (as well as combined sales) in billions of square feet, calculated on a 3/8" basis The data on plywood was obtained from Montrey and Utterback for the period 1940-1975 [20] From 1976 onwards both the plywood and OSB data were obtained from [27] Waferboard and OSB have been grouped together as a category of unveneered panels competing with plywood as in Montrey and Utterback's original paper [20] The sharp upturn in the curve for the unveneered panels in the early 1980s corresponds with the introduction of OSB Note how the plywood sales generally follows an S-curve and has a relatively uneventful life until approximately 1970 when the sales curve starts oscillating The fact that these oscillations correspond with the emergence of the unveneered panels prompts the question whether the oscillations in plywood's S-curve are causally related to the emergence of unveneered panels, i e whether the fluctuations indicate the presence of a superior substitute and are triggered by the resulting fluctuations in demand If so, it would lend credibility to the hypothesis that oscillations in the mature phase of a technology's diffusion curve indicate that it is under

attack from an emerging technology, and hence that oscillations can be interpreted as mortality indicators

Montrey and Utterback ascribe the oscillations in plywood's curve throughout the 1970s to the "... erratic nature of the overall wood products economy during that decade" They comment that "... the steep drop in the mid-1970s coincides with the nation's recession during that period, during which housing construction sank to very low levels" In order to test this statement, we now compare residential fixed investment trends in the US with plywood's S-curve The assumption is that, since the light frame construction industry is a major contributor to the residential fixed investment and this industry is one of plywood's main markets [28], an examination of the correlation between time series data for residential fixed investment and plywood sales would be a good indicator to test the hypothesis that oscillations in the curve for plywood are coupled to macroeconomic business cycles Data for residential fixed investment was obtained from Gordon [29] for the period 1950-1979, and from Statistical Abstracts of the US [30] for the period after that[1] The residential fixed investment is also shown in Figure 1 (in constant 1982 dollars) The correlation between the market swings in the curve for residential fixed investment and the oscillations in the total sales is remarkable (Note that we are looking specifically at the phases rather than the amplitudes, since we are comparing sales in billions of square feet in the case of plywood with billions of dollars in the case of residential fixed investment) Since plywood constitutes a major part of the market share, it would be fair to conclude that sales of plywood, and particularly the oscillations in its S-curve, are indeed coupled to macroeconomic business cycles, specifically residential fixed investment One should, however, be careful about the causality implied in these assumptions Does the plywood sales follow the residential fixed investment curve or is

the residential fixed investment curve driven by the plywood sales? If the latter is the case, it may be that the plywood curve oscillates for reasons other than the residential fixed investment and that the residential fixed investment only follows the plywood curve. A more plausible explanation is that the residential fixed investment in the US is determined by macroeconomic conditions and that it should be considered as a "demand" curve or driver in this setting. Surely decisions to build new housing is not determined by the amount of timber sold — rather the other way around. Timber products are supplied *inter alia* to fulfill the demand for housing and hence the plywood curve follows the residential fixed investment. It is also interesting to note how both the plywood and OSB/waferboard curves tend to track the residential fixed investment in the latest years for which the data are given. Recall that the sharp upturn in the OSB/waferboard curve in the early eighties was caused by the emergence of OSB as a technology. It would seem, however, that as OSB becomes an established technology and gains significant market share, its fortunes are also linked to residential fixed investment in a more pronounced way. The dips in the curves around 1990 illustrate this point. It will be interesting to see if OSB continues to track the oscillatory behavior of the residential fixed investment curve in years to come, and if the coupling between the plywood curve and residential fixed investment decreases as plywood loses market share.

The arguments in the previous paragraph leads one to conclude that oscillations in plywood's S-curve are primarily the result of fluctuations in the residential fixed investment pattern and therefore are not triggered by the emergence of OSB/waferboard. Hence the oscillations cannot be interpreted to be mortality indicators per se. The question does arise, however, if the emergence of the new technology contributes to some secondary or smaller perturbations in the mature technology's S-curve. To investigate this question, we now concentrate on the

S-curves of plywood and OSB/waferboard as well as the S-curve of the combined sales. Note that there are three "hiccups" superimposed on the general oscillatory pattern of plywood's S-curve (indicated with small arrows in Figure 1). At the first hiccup, the S-curve of plywood tracks the S-curve of the total sales very closely. At this point OSB/waferboard had not really made any market impact and the total sales for all practical purposes therefore represents the sales of plywood. At the second hiccup, however, the dip in plywood's S-curve is much more severe than that of the total sales and furthermore there is no hiccup at that time in the S-curve of OSB/waferboard. This could be interpreted to mean that the plywood sales lag total sales for a while, but then catches up again. It is tempting to speculate on the cause of this deviation in the plywood sales. One hypothesis might be that the demand for structured panels was being taken up by the unveneered panels rather than by plywood. The historical data in Figure 2 shows how the unveneered panels gained market share at the expense of plywood, lending support this hypothesis[2]. If this is the case, why does plywood then recover, as indicated by the plywood curve that resumes growth after the hiccup? A possible explanation is that the demand for unveneered structured panels was greater than the capacity and that the resulting slack was then taken up by plywood.

Table 1 shows the demand/capacity ratios of plywood and OSB in the US for the period 1981 to 1989 [27]. If we now focus on the period 1983-1987, which corresponds with the period where the trends in plywood sales seemed to lag the trend in residential fixed investment cycle as shown in Figure 1, we note that the industry demand/capacity ratio increased from 0.80 to 0.87 (with a high of 0.88 in 1986), i.e. 8.8%. The demand/capacity ratio for plywood increased from 0.82 to 0.84 (with a high of 0.87 in 1986), i.e. 2.4%. However, the demand/capacity ratio for OSB increased from 0.58 to 0.90 (with a high of 0.93 in 1986), i.e.

55% There is thus evidence of a much steeper increase in the demand/supply ratio for OSB than for plywood. This may indeed indicate that OSB supply was harder pushed to meet demand and hence unfulfilled orders might have been filled by plywood. Note that even though capacity was still larger than demand, there might have been regional factors, for example, that caused short term shortages in OSB. This explanation of interaction between plywood and OSB/waferboard can account for the hiccup in the plywood curve around 1985, and so lend support to the larger hypothesis that an attacking emerging technology can contribute to the perturbations in a mature technology's S-curve. In order to identify such a phenomenon, one would thus typically subtract the sales curve of the contributing technology from the total sales curve and isolate irregularities. The third hiccup seems to exhibit a similar behavior where both the total sales and that of OSB/waferboard is growing, but the sales of plywood is dipping.

Just as one tree does not make a forest, one or two hiccups in an S-curve do not constitute an oscillatory pattern. However, the arguments above support the general conclusion that an oscillatory pattern in the S-curve are not necessarily triggered by the attack from an emerging technology. What does seem plausible, however, is that an emerging technology can, together with other factors, give rise to perturbations in the S-curve (but not necessarily to oscillations). Given the arguments advanced in the previous paragraph, this statement should immediately be qualified by saying that such perturbations should be carefully analyzed within the context of other influences (such as macroeconomic business cycles) and that the mere existence of oscillations or perturbations is not enough to qualify as a mortality indicator. One of the difficulties, of course, is to distinguish between such indicators and regular statistical fluctuations. As the data on the residential fixed investment shows, the oscillations can be caused by other factors that may mask or interfere with the signals that are related to the

effects of the emerging technology Interpreting the signal thus entails more than just observing an oscillatory pattern or perturbations As this example shows, external influences such as the general economic climate and business cycles can play a significant role Taking into account measurement errors and other sources of fluctuations and oscillations mentioned, together with effects caused by business cycles, it is evident that a certain amount of signal processing will have to be done on an S-curve to extract potential signals from emerging technologies

FORECASTING THE SUBSTITUTION PROCESS

Montrey forecasted the substitution of OSB/waferboard for plywood in 1982 [26] Treating waferboard and OSB as one product category and using a Fisher-Pry model [31], he formulated the forecast in the form

$$f(t) = \frac{1}{2}[1 + \tanh \alpha (t - t_0)] \qquad (1)$$

where

$f(t)$ = fraction of takeover of OSB/waferboard in year t

α = half the initial exponential takeover rate

t_0 = year in which the substitution is 50% completed.

The constants were found to be α=0 0711 and t_0=2002, i e the forecast indicated that half the US structural panel market would be made up of unveneered panels (waferboard and OSB) by the year 2002 In their 1990 paper, Montrey and Utterback refer to the 1982 forecast, and specifically to the fact that a 14 8% substitution was predicted for 1985 whilst the true

substitution was in fact 15% [20] (However, based on the constants given in their paper, it would seem that the model given in their 1990 paper actually predicts a 8.16% substitution rather than a 14.8% substitution in 1985. Hence the rate substitution was even brisker than they predicted). Having had the benefit of several more years of historical data, the temptation of updating the forecast again was too great to resist (and in retrospect probably against the present authors' better judgment). Subsequently the substitution data of OSB/waferboard for plywood for the period 1976 to 1992 was applied in a Fisher-Pry model similar to the original one described by Montrey and Utterback. The parameters for the new forecast were determined with the software accompanying Porter *et al.*'s book [4]. Based on the new data, the coefficients for the new forecast were found to be α=0.1087 and t_0 =1995. As in the original forecast, it was assumed here that plywood and OSB/waferboard address the same market segments and that they account for the total market between them. This assumption is a rough approximation, since Montrey and Utterback state that there are mutually exclusive market segments for both plywood and OSB [20].

The new forecast is shown in Figure 2 together with the historical data as well as the original forecast. According to the new forecast, the substitution will be 50% completed in 1995. The fact that this forecast predicts a stronger current showing for OSB than is evidenced by the current historical trend is slightly worrying. However, there is strong evidence that OSB will continue to grow at the expense of plywood. As of September 1994 there were indications that at least 15 new OSB plants were likely to be build in North America before the turn of the century [32]. At the same time there is also evidence of a falling plywood production. This is in part due to the lack of raw material, environmental pressures and governmental resource management practices that have resulted in large tracts of forests no longer being available for

this purpose [33] The statement that "... New oriented strand board mills, meanwhile, have filled the void left as plywood mills shut down because they couldn't get big logs to peel. As even more oriented strand board capacity is added, it may elbow aside older plywood mills with uncertain and expensive log supplies" [34], is typical of opinions expressed in the media circa late 1994. The issue is whether capacity to manufacture OSB can be made available as fast as plywood capacity falls away [35]. As a defensive strategy, one can expect plywood manufacturers to target niche markets that are not addressed by OSB.

A chaos formulation

We now turn our attention to alternative explanations for the oscillatory behavior. This part is introduced by a discussion of a previously proposed chaos formulation, and is then followed by the presentation of a modified Lotka-Volterra model which illustrates how the symbiotic interaction of two technologies can give rise to oscillatory behavior in the mature phase of an S-curve.

Referring to the oscillatory behavior in the mature phase of some technologies' S-curves, Modis comments that "... These deviations have been explained in terms of states of chaos, which are encountered when the logistic function is put in discrete form, which becomes essential in order to analyze data via computer programs which employ iterative techniques, but it can also be justified theoretically because populations are discrete quantities after all" [24]. In another article Modis and Debecker make the comment that "... The annual rate of a population growth into a new niche had often been seen to follow a logistic pattern that brakes into fluctuations of random character and sizable amplitude just before reaching the ceiling" [22]. They then proceed to explain the oscillatory behavior of the growth curves with chaos

theory. Modis and Debecker's paper suggests a justification for an investigation into the seemingly chaotic nature of the oscillations in the mature phase of S-curves.

In addition to Modis and Debecker's contributions, several other articles have been published over the last couple of years to show the relevance of chaotic behavior and the associated use of fractals to growth models of technologies and technological forecasting (see for example Gordon and Greenspan [36,37], Bhargava *et al.* [38], Gordon [39,40] and Modis [23,41]). The conclusion that Bhargava *et al.* come to is telling of the sentiment of many of the papers, viz "... the importance of the logistic equation in describing economic and social behavior is undeniable. However, one must be prepared for the greater richness of the behavior of the solutions, particularly for large values of the nonlinearity parameter λ." [38]. The logistic equation that is referred to is the discrete difference equation form of the differential equation for which (1) is the solution, and which leads to chaotic and oscillatory behavior when λ is large (λ being a parameter analogous to α in (1)).

According to the narrative in Modis and Debecker's article [22], they happened upon the chaotic behavior whilst searching for ways in which to speed up algorithms to generate S-curves. By discretizing the calculation, they not only succeeded in generating the S-curves, but also fluctuations in both the initial and mature phases of the curve. Recognizing that the fluctuations were akin to the oscillations that are often observed on growth curves, they investigated the appropriateness of a chaos explanation for the phenomenon. They proceeded to investigate the effect by changing the nature of parameters in the discrete representation of the S-curve. Their simulations yielded systems with seemingly chaotic behavior, and hence their claim that chaos theory can account for the S-shaped growth curve, oscillations in the

mature phase of S-curves, as well as similar fluctuations often observed in the early growth phases of a technology They also suggest that chaotic behavior can exist in the transitionary period when one S-curve is replaced by another, i e when the mature phase of one growth curve is blended into the early phase of the next curve The annual production on bituminous coal in the US is held as an example

Modis and Debecker's statements that " One could reasonably expect that an upcoming growth phase in a new market niche will be heralded by precursors and, once installed, will proceed at an accelerated rhythm in the beginning", and " A well-established S-curve will point to the time when chaotic oscillations should be expected, it is when the ceiling is being approached In contrast, an entrenched chaos will reveal nothing about when the next growth phase will start" [22] deserve some comment. The notion of precursors that indicate a new growth phase is noteworthy and lends support to the hypothesis that oscillatory behavior (or perturbations) in the mature phase of technology's growth may indicate the rise of an emerging technology Drawing upon the inherent determinism in chaotic systems, Modis and Debecker seem to imply, however, that there is a certain inevitability in the onset of the chaotic oscillations Gordon alludes to the same notion when he says of chaotic oscillations generated by a simulation of sales as a function of time, " An analyst would understandably, wonder about the causes for the market swings What caused them? In fact, no externalities were responsible, all of the complex behavior of this curve results from within the system To search for externalities responsible for the market performance would be misplaced effort, for in this example, all of the chaotic behavior comes from internal sources" [40] Modis refers to Montrey and Utterback's explanations for the fluctuations in the growth curve of plywood by stating that " From 1970 onward a pattern of significant (plus or minus 20 percent)

instability appeared, which Montrey and Utterback tried to explain one by one in terms of socioeconomic arguments Given a pattern one can always correlate other phenomena to it This type of pattern, however, could have been predicted a priori by chaos formulations" [23] The arguments presented in the previous section seem to indicate, however, that the residential fixed investment did play a dominant role in determining the oscillatory behavior in plywood's S-curve

The chaos-based model that was referred to in this section describes a technology which competes against the market, i e. the formulation does not explicitly account for the effects of one or more technologies Often one finds, however, that two or more technologies are competing or are interacting with one another in a given market segment In the next section a mathematical model which involves two interacting technologies and that can also lead to oscillatory behavior, is described This model is applicable to the general case of two interacting technologies and is not restricted to the interaction of emerging and mature technologies It should be stressed that the model is presented as a conceptual one, very much in the same vein as the chaos formulation of Modis and Debecker [22], rather as one that has withstood the test of time

Modeling the oscillatory behavior with modified *Lotka-Volterra* equations

The differential equation(s) describing the diffusion of a technology must be based on the underlying mechanisms involved In order to model the diffusion characteristics of a technology, it is therefore necessary that the extent of the resources available be taken into account Finite resources are often embodied in a market niche of finite size A single equation cannot, however, describe the growth and competition of two technologies simultaneously for

it does not account for their respective effects on one another. It can at best model the diffusion of one technology into a market [42]. To model the competition of two technologies, one would need to set up a differential equation for each of the technologies based on the underlying drivers and inhibitors for that technology, together with coupling coefficients that reflect the technologies' effect on one another's growth rate. In order to address the problem at hand, it is necessary to model both the technologies explicitly, each with its own equation. They must then be coupled with coupling coefficients to account for the interaction between them. A system of differential equations rather than a single equation is therefore required. Such a system that is applicable to this problem has been formulated some time ago by the ecologists Lotka and Volterra, but until very recently was not widely applied to the diffusion of technology. The system of equations that they developed has become known as the Lotka-Volterra equations.

Several authors have shown or commented on the fact that the Lotka-Volterra equations can be successfully applied to model technological diffusion, among them Bhargava [43], Farrell [44], Marchetti [21,45], Modis [23], Nakićenović ([46] as quoted by Marchetti [45]) and Porter *et al.* [4]. Marchetti comments that "... I am fairly convinced that the equations Volterra developed for ecological systems are very good descriptors of human affairs. In a nutshell, I suppose that the social system can be reduced to structures that compete in a Darwinian way, their flow and ebb being described by the Volterra equations, the simplest solution of which is a logistic" [21].

Even though the Lotka-Volterra equations may be suitable to model technological diffusion and substitution, the question arises however, as to the appropriateness of modeling the

oscillatory behavior in the mature phase of the S-curve, with these equations. There are several references in the literature that suggest that the Lotka-Volterra equations may indeed lead to a modeling solution for the oscillatory behavior that we are concerned with here. Porter *et al.*, for example, state that "... Oscillatory models are a final class of models accommodated by the Lotka-Volterra equations. Periodic behaviors are commonly found in natural populations and they can be successfully modeled using the Lotka-Volterra equations. Oscillatory behaviors have been observed in consumption and mining patterns in the United States and in car and transportation systems in Europe. ... These growths often show a logistic start followed by an overshoot and then oscillation around a supposed limit. ... The more complex population models such as Lotka-Volterra, can represent such behaviors if the forecaster has correctly surmised their form...." [4] The above reference to a logistic equation that overshoots and then oscillates around a limit is strongly indicative of the type of oscillations that we are interested in, i.e. those that are sometimes observed in the mature phase of a technology. Recall also Marchetti's comment quoted earlier to the effect that S-curves can become oscillatory when approaching saturation and that this is a possible solution of Lotka-Volterra equations.

Consider now two technologies which are interacting in a symbiotic way. *Symbiosis* is an ecological term and refers to the association of two different organisms living attached to each other or one within the other to their mutual advantage. The term is related to the concepts of mutualism and commensualism, but for the purpose of this discussion, it is meant to imply the interaction among two technologies such that each has a positive influence on the other's growth rate. A system of nonlinear differential equations (which is based on Lotka-Volterra equations) that describes symbiotic interaction can be formulated as follows:

$$\frac{dN}{dt} = a_n N - b_n N^2 + c_{nm} NM \qquad (2)$$

$$\frac{dM}{dt} = a_m M - b_m M^2 + c_{mn} MN \qquad (3)$$

where $N(t)$ and $M(t)$ represent the "populations" of the two technologies (such as sales, for example) and all coefficients are positive This set of equations differs from traditional Lotka-Volterra equations in the sense that both a-coefficients are positive, and furthermore has been modified to depict symbiosis by having positive signs for both the coefficients that regulate the interaction among the two technologies (c_{nm} and c_{mn}). A generic phase diagram for this formulation is shown in Figure 3 The equilibrium lines on the associated phase diagram that indicate where $dN/dt=0$ and $dM/dt=0$ are respectively given by

$$N = \frac{a_n}{b_n} + \frac{c_{nm}}{b_n} M \qquad (4)$$

$$N = \frac{b_m}{c_{mn}} M - \frac{a_m}{c_{mn}} \qquad (5)$$

The axes of the phase diagram are also equilibrium lines, i e $dM/dt=0$ on the N-axis where $M=0$ and $dN/dt=0$ on the M-axis where $N=0$. The equilibrium point (N^*,M^*) represents the position where $dN/dt=0$ and $dM/dt=0$ simultaneously (i e the intersection between these two lines) and is normally a stable point, in the sense that once it has been reached, the trajectory will terminate there The arrows in the four subregions of the phase diagram indicate the directional derivatives in those regions Note that time is a parameter for a trajectory on the phase diagram

Pielou's iterative solution for the set of equations [47] are modified to account for the symbiotic interaction, yielding the solution

$$N(t+1)=\frac{\lambda_n N(t)}{1+\beta_n N(t)-\left(\dfrac{c_{nm}}{b_n}\right)\beta_n M(t)} \tag{6}$$

where

$$\lambda_n=e^{a_n} \tag{7}$$

$$\beta_n=\frac{b_n(e^{a_n}-1)}{a_n} \tag{8}$$

and

$$M(t+1)=\frac{\lambda_m M(t)}{1+\beta_m M(t)-\left(\dfrac{c_{mn}}{b_m}\right)\beta_m N(t)} \tag{9}$$

where

$$\lambda_m=e^{a_m} \tag{10}$$

$$\beta_m=\frac{b_m(e^{a_m}-1)}{a_m} \tag{11}$$

In order to illustrate the dynamics of this formulation, consider now the system

$$\dot{N}(t)=N(0.1-0.01N+c_{nm}M) \tag{12}$$

$$M(t) = M(0.15 - 0.01M - c_{mn}N) \quad (13)$$

with c_{mn} 0.005 and c_{nm} 0.005 Let the initial conditions be $M(0)=1$ and $N(0)=15$ It should be stressed that the numeric values of the coefficients as well as the initial values are not intended to relate to any real situation — the coefficients a and b in this example were randomly chosen with c adjusted to illustrate the dynamics conceptually The resulting time domain plot and associated phase diagram are shown in Figures 4 and 5 Note how the trajectory on the phase diagram approaches and terminates on the equilibrium point

Coming back to the oscillatory behavior in the mature phase of an S-curve, we note that an interesting phenomenon occurs when $c_{mn}c_{nm}$ approaches $b_n b_m$ Consider again the phase diagram in Figure 3 As expected, a trajectory that initiates in subregion I approaches the equilibrium point However, rather than terminate at the equilibrium point (as in Figure 5), the trajectory seems to overshoot and then breaks into an oscillatory pattern. A cursory inspection of the oscillatory pattern in the time domain reminds one of a chaos-like state. Figures 6 and 7 show the time domain plot and phase diagram when c_{mn}=0.005 and c_{nm}=0.0157, yielding values of $b_n b_m$=0.0001 and $c_{nm}c_{mn}$=0.000079 (whereas in the previous case $c_{nm}c_{mn}$=0.000025) Both technologies live fairly uneventful lives in the time domain, following regular growth along S-curves until approximately t=240 when they both break into chaos-like oscillatory patterns By examining the time domain plot in Figure 6, one might wonder what gives rise to the sudden burst of oscillations in the mature phase after the two technologies coexisted for a long time during which both followed normal logistic growth It turns out that there is nothing mystical about the time when the oscillations start An examination of the associated phase diagram in Figure 7 reveals that the time when the

oscillations start corresponds with the time when the trajectory in the phase diagram reaches the equilibrium point If the coefficients are known, the phase diagram can be constructed and subsequently the time when the oscillations will commence can be predicted

The chaotic oscillations observed here are a far cry from those shown in Figure 1 Note that the two technologies simulated in Figure 6 break into oscillations simultaneously — something that plywood and OSB/waferboard in Figure 1 do not do Keep in mind, however, that the system shown here is purely to illustrate the concept, and that the possibility that the plywood/OSB/waferboard case cannot be modeled with this model should not be dismissed out of hand without further investigation of the behavioral characteristics of the model It should also be kept in mind that the simulated results presented here were generated with a difference equation and the time increments in the model hence plays an important role in the behavior, particularly when a chaotic situation occurs. Note that the model also sometimes yields negative values for N and M, something that cannot occur if N and M represent the real sales of the technologies for example, where we assume $M,N>0$. Nevertheless, the results obtained here indicate that, in principle, one can expect oscillatory behavior in the mature phase of S-curves *under certain circumstances* when two technologies have a symbiotic interaction From the nature of equation (1) we know that in the absence of another technology, oscillatory behavior does not occur and hence we can infer that (within the realms of the model), the chaos-like oscillations in the mature phase of the S-curve can also be caused by symbiotic interaction among multiple technologies, in which case the onset of chaos depends very strongly on the ratios of the coefficients in the underlying Lotka-Volterra equations

Note that the system modeled above changed its behavior from stable to oscillatory when the ratios of the coefficients changed (i e the change depicted in Figures 4 and 5 versus that in Figures 6 and 7) In general, one can assume that the coefficients will be time dependent rather than constant, and furthermore that external forces can and will influence their values dynamically with time It is then entirely conceivable that a chaotic solution may result if the values of the coefficients change relative to one another to support such a solution This brings us back to the issue of the *pre-determinedness* of the chaotic nature that has been discussed in the literature The issue boils down to the question whether the growth curve that a particular technology exhibits is genetically encoded into the technology (similar to the growth of some animate or organic objects, for example) If one takes the view that technological diffusion and substitution are social rather than natural phenomena, there is an argument to be made that there is no predetermined inevitability in the growth of technology The diffusion pattern and particularly the rate of diffusion, are determined by various external factors, although we certainly acknowledge that the inherent characteristics of the innovation or technology can influence these factors We must also not exclude the possibility that, from a modeling viewpoint, the growth of a particular technology may be described by different models along its growth path, as suggested by Tingyan [48], for example. It is quite feasible that the growth may be described by the general Lotka-Volterra equations as suggested by Bhargava, where the coefficients of the equations change with time as they are acted upon by external forces [43] Depending on the relationship and ratios between the coefficients, the system may then exhibit smooth growth, oscillatory or even chaotic behavior in various phases of the growth cycle These will be dictated by the ratios of the coefficients at any given moment as they, in turn, are influenced by external forces Even though some technological growth

patterns may exhibit chaotic oscillations, the question that should be asked is, "What drove the system to chaos?" [39]

Conclusions

The paper started by discussing the notion of mortality indicators that signal the demise of mature technologies The question was posed whether the oscillations that have been observed in the mature phase of some technologies' S-curves are indications that such technologies are being attacked by emerging technologies, i e whether the oscillations are mortality indicators The case of the substitution of plywood by OSB/waferboard was investigated, and it was shown that the oscillations in plywood's S-curve track the phases of the residential fixed investment in the US. Hence it is concluded that the residential fixed investment pattern is therefore primarily responsible for the oscillations and that the oscillations are not mortality indicators The rise of OSB/waferboard does, however, seem to contribute to perturbations in the mature technology's S-curve (plywood in this case) A further conclusion can thus be made that the emergence of a new technology can have a contributory influence on perturbations in a mature technology's S-curve, although the oscillations can be dominated by other effects such as macroeconomic business cycles Given the fact that accurate and reliable mortality indicators can have profound managerial implications and that the surface has only been scratched in this paper with regard to death knells of mature technologies, further pursuit of the notion of mortality indicators is certainly to be recommended. One avenue of research may be the application of signal processing techniques to "extract" potential signals that are caused by emerging technologies

There have been some comments in the literature that the oscillatory behavior may be a chaos related phenomenon The chaos formulation was used as a backdrop to introduce a mathematical model which is based on modified Lotka-Volterra equations This model assumes symbiotic interaction among two technologies (i e. where each has a positive effect on the other's growth rate), and it is shown that this type of interaction can also give rise to oscillatory behavior in S-curves under certain circumstances, depending on the ratios of the coefficients It is suggested that this is another avenue of research which may lead to interesting and useful results

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FOOTNOTES

1 The data from the US Statistical Abstracts [30] is given in constant 1987 dollars A deflator of 1 174 was used to convert it to constant 1982 dollars [29]

2 The historical data in Figure 2 was obtained by calculating market share from the values in Figure 1, assuming that plywood and OSB/waferboard make up the total market as in [20]

FIGURE LEGENDS

Figure 1 US sales of plywood and OSB waferboard as well as residential fixed investment (in constant 1982 dollars) The dark arrows indicate the hiccups discussed in the text

Figure 2 Market share of OSB/waferboard versus plywood in the US

Figure 3 Generic phase diagram for the symbiotic system with an equilibrium point (N^*,M^*) in the region $M,N>0$ $(b_n b_m > c_{nm} c_{mn})$ The dark arrows indicate the directional derivatives in the various subregions

Figure 4 Time domain plot for two technologies in symbiotic interaction ($c_{mn}=c_{nm}=0\ 005$)

Figure 5 Phase diagram for two technologies in symbiotic interaction ($c_{mn}=c_{nm}=0\ 005$) Note how the trajectory terminates on the equilibrium point

Figure 6 Time domain plot for two technologies in symbiotic interaction ($c_{mn}=0\ 005$ and $c_{nm}=0\ 0157$) Note the onset of oscillations in the mature phase in the region of $t=240$

Figure 7 Phase diagram for two technologies in symbiotic interaction with oscillations in the mature phase ($c_{mn}=0\ 005$ and $c_{nm}=0\ 0157$) Note the onset of the oscillatory behavior after the trajectory crosses the equilibrium point

Table 1 Demand/capacity ratios for plywood and OSB in the US for the period 1981-1989 (3/8" basis) [27]

Figure 1: US sales of plywood and OSB/waferboard as well as residential fixed investment (constant 1982 dollars). The dark arrows indicate the hiccups discussed in the text.

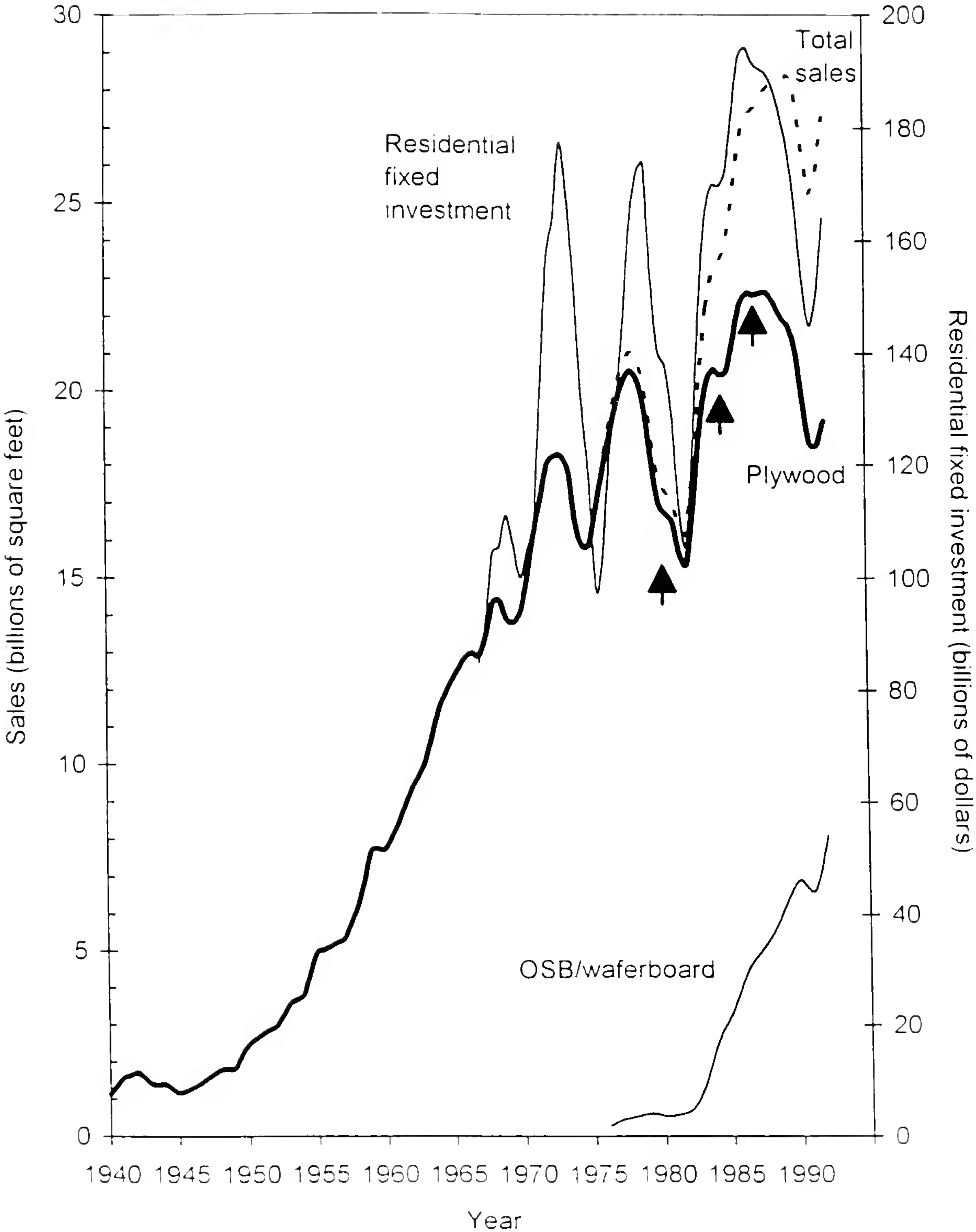
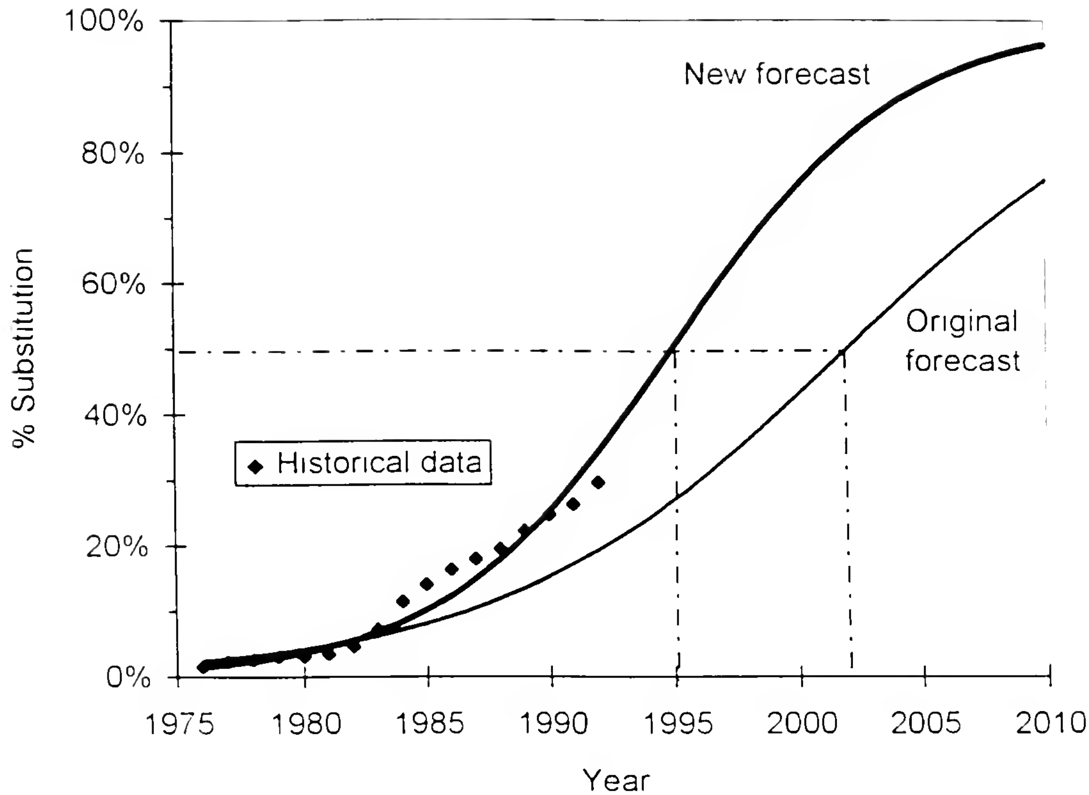


Figure 2: Market share of OSB/waferboard versus plywood in the US



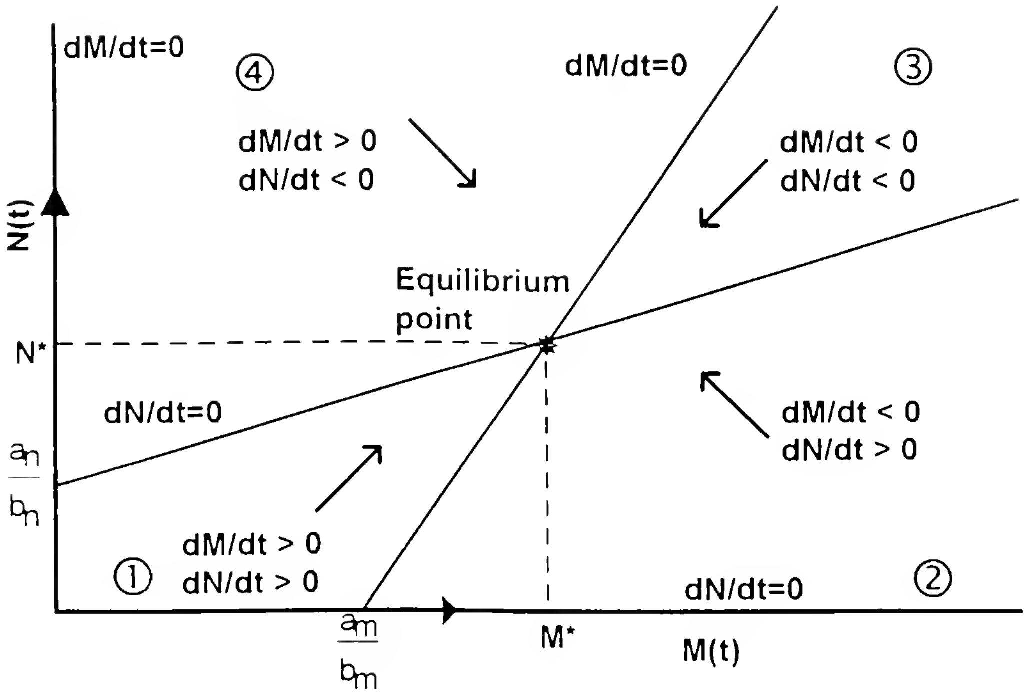


Figure 3: Generic phase diagram for the symbiotic system with an equilibrium point (N^*, M^*) in the region $M,N>0$ $(b_n b_m > c_{nm} c_{mn})$ The dark arrows indicate the directional derivates in the various subregions

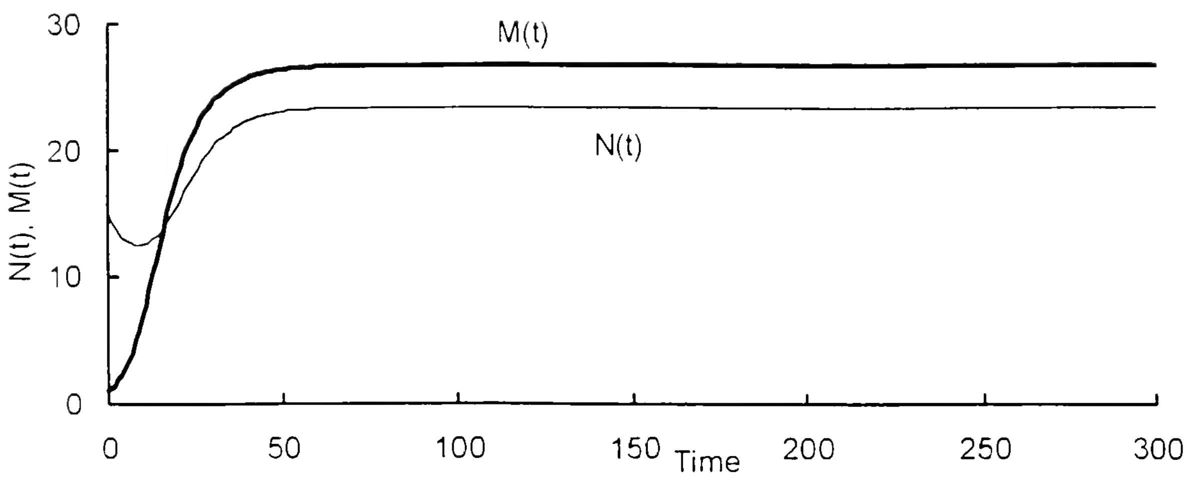


Figure 4: Time domain plot for two technologies in symbiotic interaction ($c_{nm}=c_{mn}=0.005$)

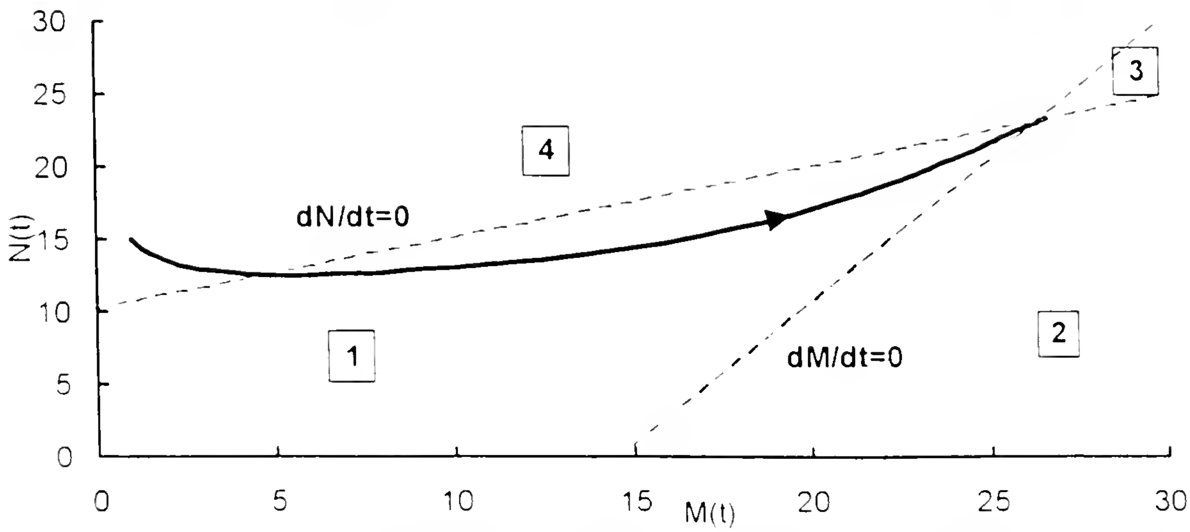


Figure 5: Phase diagram for two technologies in symbiotic interaction ($c_{nm}=c_{mn}=0.005$)
Note how the trajectory terminates on the equilibrium point

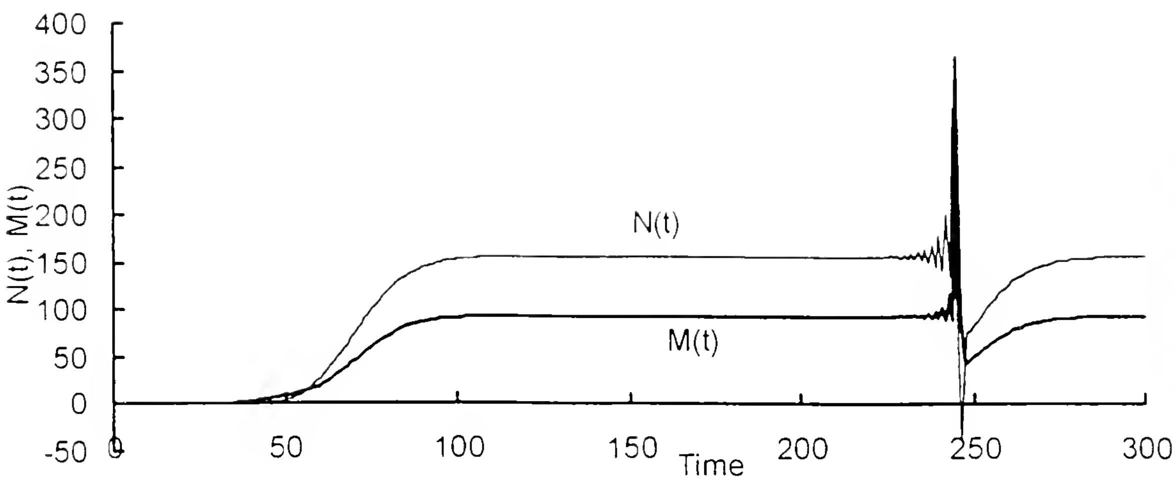


Figure 6: Time domain plot for two technologies in symbiotic interaction (c_{mn}=0 005 and c_{nm}=0 0157) Note the onset of oscillations in the mature phase in the region of t=240

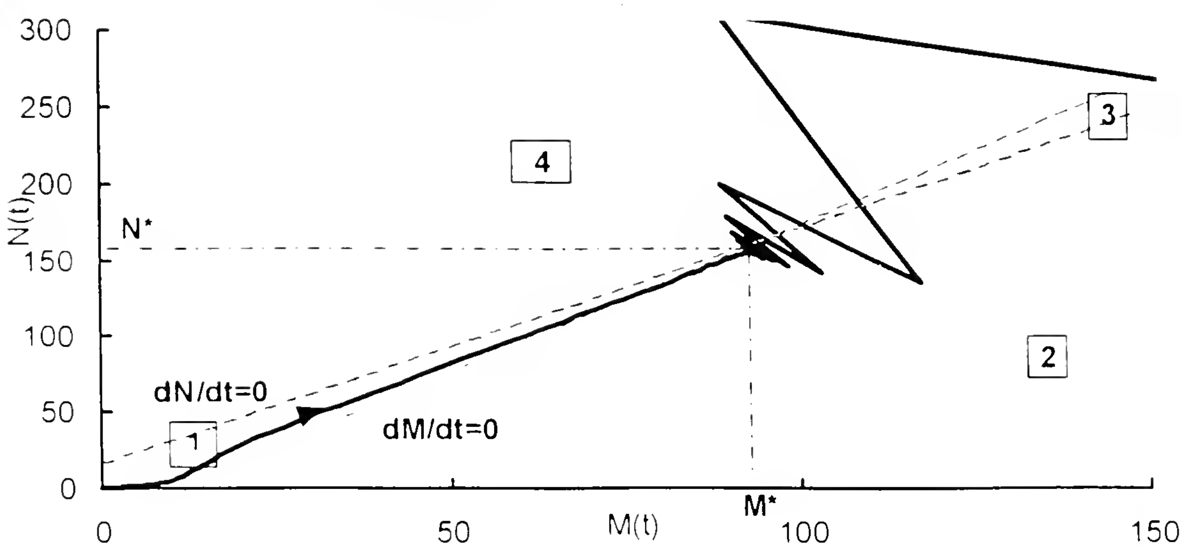


Figure 7: Phase diagram for two technologies in symbiotic interaction with oscillations in the mature phase (c_{mn}=0 005 and c_{nm}=0 0157) Note the oscillatory behavior after the trajectory crosses the equilibrium point (N^*,M^*)

Table 1: Demand/capacity ratios for plywood and OSB in the US for the period 1981-1989 [27]

	1981	1982	1983	1984	1985	1986	1987	1988	1989
Plywood	0.74	0.69	0.82	0.86	0.84	0.87	0.84	0.86	0.86
OSB	0.48	0.49	0.58	0.79	0.76	0.93	0.90	0.88	0.90
Total	0.71	0.68	0.80	0.82	0.83	0.88	0.87	0.88	0.89

FOOTNOTES

1 The data from the US Statistical Abstracts [30] is given in constant 1987 dollars. A deflator of 1.174 was used to convert it to constant 1982 dollars [29]

2 The historical data in Figure 2 was obtained by calculating market share from the values in Figure 1, assuming that plywood and OSB/waferboard make up the total market as in [20]

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